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Influence of a short term heat treatment by conduction and induction on the mechanical properties of AA6014 alloys

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Abstract

Tailored heat treated blanks are a well-known approach to enhance the formability of 6000-series aluminum alloys. The desired strength and ductility distribution can be adjusted by laser, induction or conduction heating. The present work investigates the influence of short term conduction and induction heat treatments on the mechanical properties of AA6014 aluminum alloys. The reduction in yield strength and uniform elongation is compared with literature data from laser heating. Additionally, the homogeneity of the temperature distributions and heating rates are evaluated. The results indicate that by conduction heating the uniform elongation is less influenced as by laser and induction heating, due to a higher homogeneity of the temperature distribution.

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Keywords: THTB; conduction; aluminum; mechanical properties; sheet metal, AA6014; temperature homogeneity

1. Introduction

The increasing world population, global warming and diminishing resources have led to high environmental awareness in the automotive industry. A promising approach to decrease the total energy demand of a car is lightweight construction (Friedrich and Hülsebusch 2009). Aluminum based alloys offer a great potential for weight reduction, due to their good strength to weight ratio (Merklein et al. 2014). For outer panels, Al-Mg-Si alloys (6xxx)

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are commonly used in the automotive industry because of their ability to be age-hardened (Miller et al. 2000). However, the formability of these alloys must be considered as relatively limited, especially in comparison to steels. Thus, a simple substitution of heavier materials with aluminum alloys is often not possible. One approach to enhance the forming limits is the use of tailored heat treated blanks (THTB) (Merklein et al. 2009). THTB are based on the idea to expose the material locally to a short term heat treatment. By this, a strength and ductility distribution is created which can be optimized for a specific forming operation (Merklein and Vogt 2007). The blank is softened in areas of plastification, while the area where the punch force is applied is not softened. The improved material flow to crack critical areas lowers the necessary forming force (Geiger et al. 2009). Consequently, occurring stresses during the deformation are lower and the formability of the blank is improved (Merklein and Vogt 2007). In dependence of the maximum temperature applied, different grades of softening can be obtained. On a microstructural basis this is explained by the dissolution of (co-)clusters and GP-zones (Geiger et al. 2009). To ensure softening of the material, the heating rate must exceed a critical value (Hofmann 2002). Such heating rates can for example be reached by laser heating (Kerausch 2007). As alternatives to produce THTB, heat conduction and induction is mentioned by various authors, e.g. Hogg (2006). A comparison of the three methods, as reported by Geiger et al. (2009), is given in Table. 1. From an industrial point of view heat conduction is of special interest, since one can expect very good reproducibility, a homogenous temperature distribution and high productivity. However, no publication is available so far, in which technological differences of the heating methods are linked to mechanical properties. Thus, the present work investigates the influence of short term heat treatments by conduction and induction on the mechanical properties of AA6014 alloys. At the end, the results are discussed under consideration of literature data from laser heated aluminum alloys. The aim of this work is an evaluation of different heating methods to produce THTB in view of industrial applications.

Table 1. Comparison of laser, induction and conduction heating to produce THTB as reported by Geiger et al. (2009), rated between unfavorable (– – –) and favorable (+ + +).

Category	Laser	Induction	Conduction
Heating rate	+ + +	+ + +	+ +
Homogeneity of the temperature distribution	0	– –	+ + +
Reproducibility	0	–	+ + +
Possibility of a holding time	– – –	–	+ + +
Investment costs – machine	– – –	0	0
Investment costs – tools	+ + +	– –	– –
Set up time	+ + +	– –	0
Productivity	– –	+ + +	+ + +

2. Experimental

2.1. Material and sample preparation

Specimens for tensile testing (A80) were prepared from commercially available AA6014 aluminum sheets in state T4. The chemical composition of the investigated alloys was determined by optical emission spectroscopy and is given in Table 2. Alloy 1 was used for heat treatments by conduction and alloy 2 for induction respectively. All specimens were obtained from an orientation 90° to the rolling direction of the sheet. The thickness d_0 of both alloys is given in Table 2.

Table 2. Chemical composition (wt.-%) of the investigated alloys determined by optical emission spectroscopy and thickness (mm) as given by the supplier.

Alloy	d_0	Al	Si	Mg	Fe	Cu	Mn	V	Ti	Cr	Zn
1	1.15	≈ 98.35	0.554	0.625	0.209	0.108	0.075	0.0395	0.016	0.009	0.011
2	1.00	≈ 98.27	0.615	0.645	0.170	0.124	0.076	0.0285	0.023	0.012	0.004

2.2. Heat treatment

The tensile test specimens were exposed to different heat treatments by conduction and induction. A schematic illustration of a time-temperature profile is shown in Fig. 1a. The maximum temperature T_{max} was varied between 100°C and 400°C and is reached in the time t_{heat}. For cooling, the specimens were self-quenched at room temperature ($T_{storage}$ = 25°C) for the time $t_{storage}$.

Conduction heating was carried out in a pneumatic press with four ceramic heating elements at top and bottom of the tool (cf. Fig 1b). The bottom part of the tool including the heating elements and a specimen is visualized in Fig. 1c. Each heating element has a size of 80 x 80 mm. Between two elements is a small gap of 5 mm, to avoid any damage due to thermal expansion.

Fig. 1. (a) Schematic illustration of the time-temperature profile of a specimen (b) Pneumatic press with top and bottom heating tool and the control unit for the heating elements; (c) schematic illustration of the bottom tool including four heating elements.

The ceramics were pre-heated to the maximum temperature before the specimen was inserted. After inserting, the press was closed for 3 seconds with a force of 1.1 kN. Five samples were prepared for each maximum temperature. To ensure that the set temperature value was reached, a specimen with thermocouples was measured as reference. The positions of the thermocouples are shown in Fig 2a. Additionally, the temperature homogeneity of the specimen was evaluated using an infrared camera. For this purpose, the specimen was coated by a white layer with constant emission coefficient ε. For the given viewing angle in the press, ε was determined as 0.78.

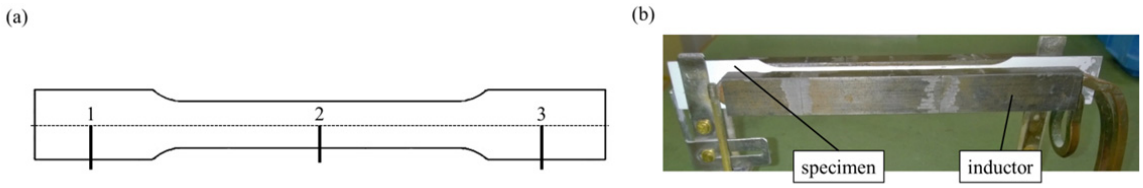

Fig. 2. (a) Illustration of the positions for the thermocouples in the white coated tensile test specimen used for thermal imaging; (b) Inductor geometry for tensile test specimens.

For induction heating an inductor was chosen which is specifically designed for tensile test specimens (cf. Fig. 2b). The geometry is optimized to achieve high temperature homogeneity. The time t_{heat} was set to 4.5 s and the temperature was tracked using an infrared camera. Thus, the specimens were also coated by a white layer with constant emission coefficient ε, determined as 0.90.

2.3. Reference values and tensile tests

Besides the short term heat treatments, three tensile test specimens were solution heat treated for 30 minutes at 540°C using an air furnace (state W). Since this state corresponds to dissolution of all precipitates in the microstructure, these samples are used as reference for a fully softened state.

Tensile tests were performed 15 minutes after the heat treatments (= $t_{storage}$) and in state T4 and W. All tests were conducted at room temperature following DIN EN ISO 6892.

3. Results

3.1. Heating rate and temperature homogeneity of the samples heated by conduction

Fig. 3 shows the measured time-temperature curves of the thermocouples in solid lines and the corresponding heating rate with dashed lines. The heating elements were set to a temperature of 350°C.

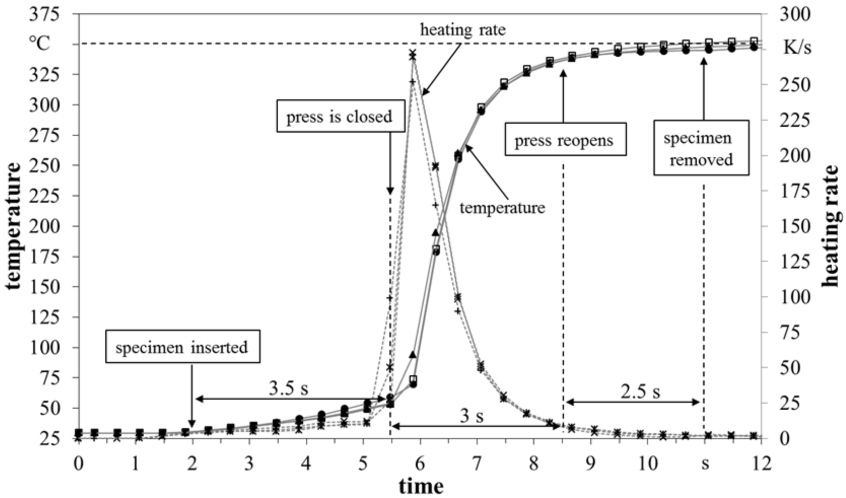

Fig. 3. Measured time-temperature profiles for the three thermocouples and corresponding heating rates over time.

After inserting the specimen, the temperature rises slowly until the press is closed. In the closed state, the temperature increases strongly and the specimen reaches almost 350°C. The target temperature is attained, by the time the press is reopened and the specimen is removed. The heating rate over time is also shown in Fig. 3. As can be seen, a maximum of approximately 275 K/s is reached immediately after the press is closed. The following decline in heating rate is attributed to the decline in temperature gradient between heating elements and specimen. Since the measured data of the three thermocouples differs only slightly from each other, overall temperature homogeneity is expected. In Fig. 4a a thermal image of the specimen is shown immediately after opening the press.

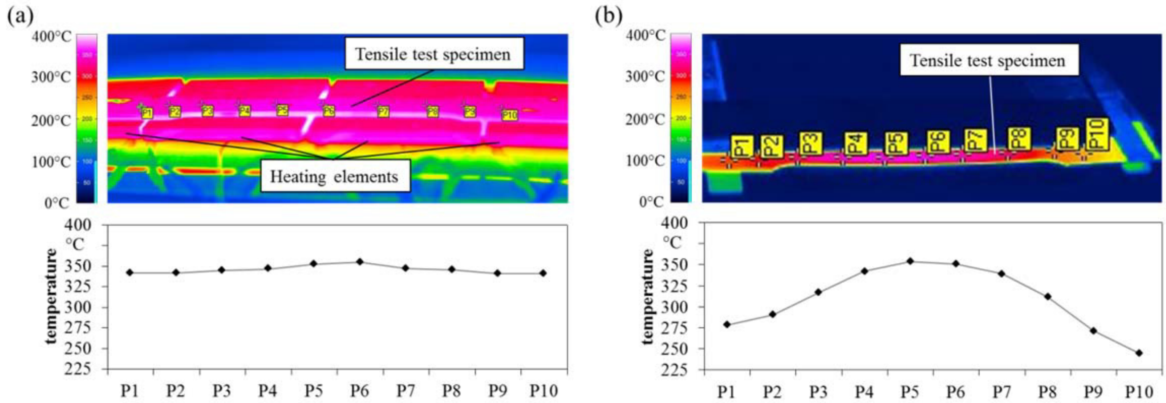

Fig. 4. (a) Thermal image of the specimen heated with conduction immediately after opening the press (b) thermal image of the specimen heated with induction at the maximum temperature.

It must be mentioned that only the specimen was coated by a white layer with constant emission coefficient, whereas the surfaces of the heating elements were left untreated. Thus, the temperature of the heating elements is not correctly displayed in the image. Evaluating by colour, the specimen is homogeneously heated to a temperature of around 350°C. To verify the homogeneity, 10 data points were selected along the longitudinal axis of the specimen. In Fig. 4a the position of the points are marked by labels from P1 to P10. The minimum value was measured in P9 with 340.6°C and the highest in P6 with 354.5°C. The average value of all 10 data points is 345.4°C with a standard deviation of 4.8°C.

3.2. Heating rate and temperature homogeneity of the samples heated by induction

In Fig. 5 the time-temperature profile of the specimen heated by induction is shown for a maximum temperature of 350°C. The applied heating rate is shown with a dashed line for the mean temperature. An increase with time is observed, until a value of 90 K/s is reached after 3.5 s. The three solid lines refer to the minimum, maximum and mean temperature measured over the gauge length of the specimen. As can be seen, the mean and minimum temperatures do not reach the target temperature within the time t_{heat} = 4.5 s. Under consideration of the thermal image at T_{max} given in Fig 4b, this is explained by an inhomogeneous temperature distribution. Caused by the geometry of the inductor, a decrease in temperature is observed outside the gauge length of the specimen. As done for the samples heated by conduction, 10 data points were selected along the longitudinal axis of the specimen. For an evaluation of the temperature homogeneity only the points P3 to P8 were taken into account. The maximum temperature of 353.9°C was measured in P5 and the minimum temperature in P3 with 316.9°C. The average value of the 6 data points is 335.8°C ± 17.5°C.

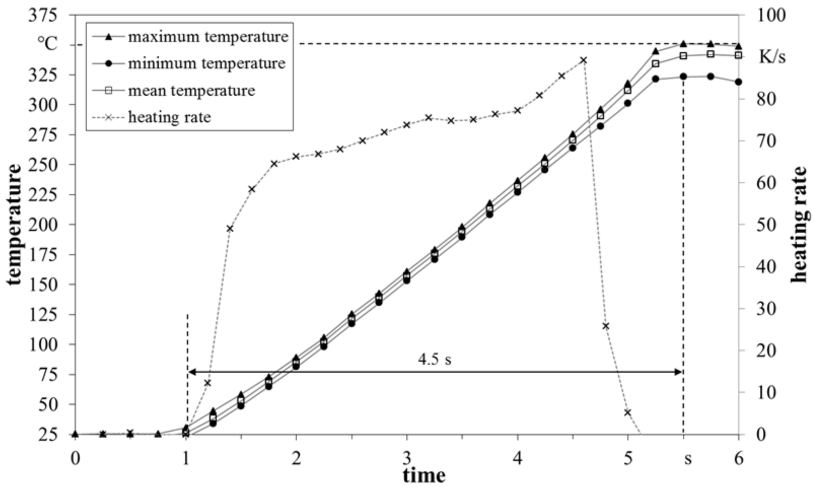

Fig. 5. Time-temperature profile and heating rate of the mean temperature measured with thermal imaging for the induction heated specimen.

3.3. Mechanical properties for different maximum temperatures

Fig. 6 shows the measured yield strength and uniform elongation in dependence of the maximum temperature for both heating methods. In addition, the corresponding values for the state T4 and W are shown in the figure. The tensile strength is not plotted since the curve shows the same trend as the yield strength, but is shifted to higher values. Respectively, the elongation at fracture correlates with the values of uniform elongation and is thus also not shown.

The yield strength remains at the T4-level up to a maximum temperature of 200°C for both heating methods. A further temperature increase results in a gradual decline of the yield strength until at 400°C the same value as for the material in state W is obtained. For the same maximum temperature, the induction heated material shows lower yield strength values than after conduction heating. The uniform elongation of the conduction heated material remains at the T4-level up to a maximum temperature of 200°C and then decreases until a minimum value of around 16 % is reached at 275°C. For the induction heated material the decline is already observed from maximum temperatures higher than 100°C. The minimum of 15 % is reached at 250°C. To higher maximum temperatures the uniform elongation increases again to around 20 % for both heating methods. Another observation is that in comparison to conduction heating the standard deviations are considerably higher for the induction heated material.

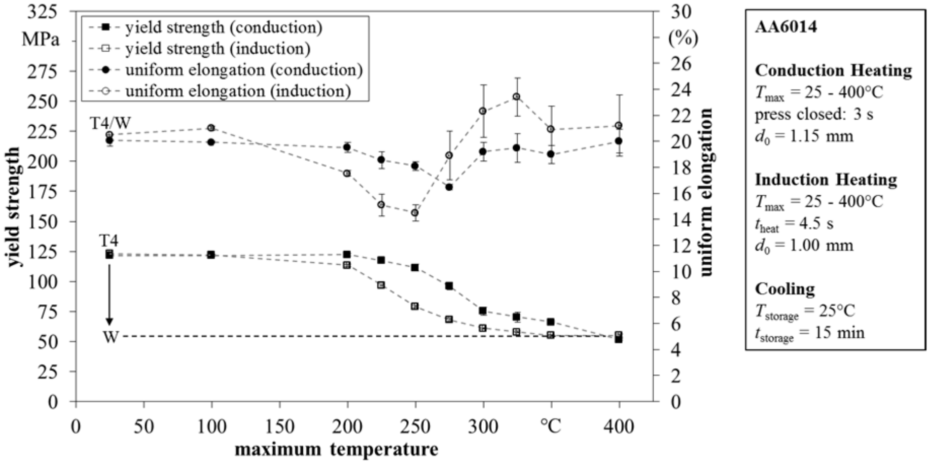

Fig. 6. Yield strength and uniform elongation in dependence of the maximum temperature applied in the short term heat treatment by conduction and induction.

4. Influencing the mechanical properties by conduction in comparison to laser and induction heating

Fig. 7a shows the relative reduction in yield strength based on the state T4 as obtained in this work for induction and conduction heating. Respectively, the uniform elongation is shown in Fig 7b. In addition, literature data for laser heated material is given in Table 3. In each case, the values were approximated from diagrams for the highest reduction in yield strength and for the minimum uniform elongation. The relative reductions were calculated with regard to the reference state T4.

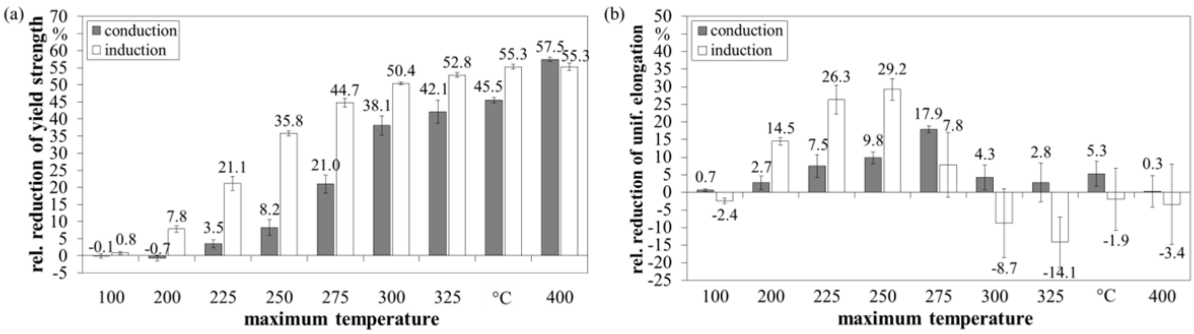

Fig. 7. (a) Relative reduction in yield strength and (b) uniform elongation based on the state T4 for conduction and induction heating.

The relative reduction in yield strength is higher for induction than for conduction heating for all investigated maximum temperatures except 400°C. The discrepancy reduces to higher maximum temperatures and is possibly attributed to the difference in the applied time-temperature profiles and obtained temperature distributions (cf. Fig 3-5). The maximum relative reductions in yield strength from laser heated materials as given in Table 3 vary from around 35 % to 46 %. Compared to results from this work, this adds up to a difference of 9 – 22 %. Assuming a yield strength of 110 MPa in state T4, such a difference corresponds to 10 – 25 MPa. This indicates that for high maximum temperatures the relative reduction in yield strength is in the same order of magnitude for all heating methods and alloys. The remaining differences are likely attributed to chemical compositions and the used time-temperature profiles. Geiger et al. (2009) investigated the mechanical properties of an AA6181PX heated by laser and conduction. However, the variation in yield strength by heating method was not as strong as observed in this work. This indicates that the present time-temperature profile is not fully optimized to achieve a maximum reduction in yield strength.

Table 3. Relative reduction in yield strength and uniform elongation as reported in literature.

Author	Alloy	d_0 (mm)	Heating method	t_{heat} (s)	T_{max} (°C)	relative reduction based on T4 (%)	
						yield strength	uniform elongation
Geiger et al. (2009)	AA6181PX	1.15	laser	< 3.5	400	42.0	3.8
					340	28.6	26.8
			conduction	< 4.5	400	35.7	4.7
					350	28.6	21.6
Merklein et al. (2007)	AA6181PX	1.15	laser	< 3.5	380	34.5	5.5
					290	16.6	44.4
Merklein et al. (2012)	AA6016	1.0	laser	< 1.8	400	46.0	24.0
					250	25.9	48.0
this work	AA6014	1.15	conduction	< 9s	400	57.5	0.3
					275	21.0	17.9
		1.00	induction	< 3.5	400	55.3	- 3.4
					250	35.8	29.2

The relative reduction in uniform elongation obtained in this work is considerably lower for conduction heating than for induction heating. As for the yield strength, the differences decrease to higher maximum temperatures (under consideration of the standard deviations). This observation can likely be explained by the temperature homogeneity of the specimens. On the one hand, with conduction heating a temperature distribution with a variance of approximately 10°C was measured. On the other hand, induction heating showed a variance in temperature of 35°C. At high maximum temperatures a large variance does not have significant impact on the mechanical properties, since the main microstructural mechanism is the dissolution of clusters. To put it another way, regarding phase changes it does not make a difference if a maximum temperature of 400°C is reached with a variance of 35°C or 10°C. However, at lower maximum temperatures at which transitional processes occur in addition to dissolution, the variance in temperature results in an inhomogeneous microstructure. With a view to uniform elongation, this is an unfavourable state of the material, thus the relative reduction is higher for induction heating (inhomogeneous) in comparison to conduction heating (homogeneous). Microstructural inhomogeneity is probably also the reason for the higher standard deviations observed for induction heating. For laser heating, the maximum relative reduction in uniform elongation varies between 26.8 % and 48 %. In this work, a maximum reduction of 17.9 % was measured for conduction and 29.2 % for induction. While the value for induction fits well in the range reported for laser heated materials, the reduction for conduction is around 9 % to 30 % lower. Assuming a uniform elongation of 20 % in state T4 such a reduction corresponds to an absolute difference up to 6 %. As stated above, the variation is likely explained by the higher temperature homogeneity of the conduction heat treatment in comparison to laser and induction heating. This explanation is supported by published data from Geiger et al. (2009), in which the same material showed a higher uniform elongation after a conduction heat treatment in comparison to laser heating. In other words, the decrease in uniform elongation can be minimized with higher homogeneity of the temperature distribution. This is an interesting result with regard to any industrial applications of THTB, since lower maximum temperatures are a way to reduce the overall process costs. Besides, thermal distortion is minimized which might affect automated production.

Essentially, the influence on the mechanical properties by conduction is the same as it is for any other heating method. As observed by laser or induction heating, the yield strength declines with increasing maximum temperature while the uniform elongation passes through a minimum. This is in good agreement with the microstructural models given in literature, which describe the influence on the mechanical properties by the formation and dissolution of precipitates (Merklein et al. 2012). Depending on the maximum temperature, respectively the dissipated energy, the phases in the microstructure are changed according to the precipitation sequence (Edwards et al. 1998). In principal, it should thus be possible to obtain the same mechanical properties for a specific maximum temperature regardless of the heating method. However, variations in the mechanical properties with the heating method are observed in this work and also reported in literature (Geiger et al 2009). Most likely, these variations are attributed to technological differences arising from the chosen heating method such as the time-temperature profile, reproducibility and/or the homogeneity of the temperature distribution. From an industrial point of view it seems promising to use conduction heating, especially because of the minimized influence on uniform elongation.

5. Conclusion and Outlook

The present work investigated the influence of a short term heat treatment by conduction and induction on the mechanical properties of AA6014 aluminum alloys. The results show variations in mechanical properties with the heating method. Likely, this can be explained by technical limitations of the heating technologies, e.g. heating rate, temperature homogeneity, etc. (cf. table 1). Consequently, the same mechanical properties are only obtained when a material is exposed to exactly the same time-temperature profile. The results indicate that the uniform elongation is positively influenced by a higher homogeneity of the temperature distribution. Conduction seems thus promising for an industrial application of THTB. However, the used heating parameters in this work do not lead to a maximum reduction in yield strength. Future work will thus be conducted to optimize the heating parameters with regard to obtain minimal yield strength while keeping the uniform elongation as high as possible.

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